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TITLE **EQUATION OF STATE AND CRUSHING DYNAMICS OF LOW-DENSITY SILICA AEROGELS**

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EQUATION OF STATE AND CRUSHING DYNAMICS OF LOW-DENSITY SILICA AEROGELS

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Shock compression of low-density silica aerogels reveals a rate process associated with the crushing dynamics of the aerogel structure. Embedded magnetic impulse velocity gauge (MIV) experiments have been accomplished on density 0.3 and 0.12 g/cm^3 materials. The crushing rate has been determined for the low pressure (~ 0.1 to 0.2 GPa) regime, and equation of state (EOS) data have been acquired. The crushing rate increases with applied pressure in this low pressure region.

1. INTRODUCTION

We have undertaken an experimental program to investigate the potential of silica aerogels as low shock impedance materials for use in the determination of low-pressure equations of state (EOS) of high explosives. This necessitates a study of the shock-based EOS of the aerogels. The results of this study to date are reported in this paper.

1.1 Aerogels

Aerogels are coherent expanded solidified gels with the liquid phase removed. The process for production of such materials has undergone continuous improvement and modification since first being discovered by Kistler.[1] The materials used in this study are SiO_2 of initial densities 0.3 and 0.12 g/cm^3 with, about 1% impurities of hydrogen and carbon. The samples were obtained from the Lawrence Livermore National Laboratory and MST-7 at Los Alamos National Laboratory.

1.2 Preparation

The samples were machined to shape for the insertion of the embedded magnetic impulse velocity (MIV) gauge used for these experiments.[2] The initial shape is a right circular cylinder approximately 54 mm diameter by 35 mm high. A chord is drawn on one face approximately 1/3 of a diameter in from the edge and a saw cut made, with the blade oriented along the chord, and at an angle of approximately 60° to the axis of the cylinder. This produces a nominally 30° wedge off the face of the cylinder that provides the mounting surface for the multi-element gauge. After the gauge is mounted, the wedge is replaced over the gauge and the sample appears to be a cylinder once again with the gauge leads exiting from the side of the cylinder. Great care must be taken in assembly as the aerogels are quite fragile - breaking like glass with very little applied force.

1.3 Difficulties

The fragility of the samples leads one to be very careful in gluing the gauge package into the sample. Care to avoid fracture may lead to large assembly gaps of the order of the gauge thickness or more. These gaps manifest themselves in the data in somewhat unpredictable ways and more discussion of such behavior will occur later in this paper. In addition to the gluing problems, one must be cautious of the type of glue used as these materials are also quite sensitive to absorbing any liquid.

2. EXPERIMENTS

The samples, prepared as described above, are affixed to a target plate with a series of tilt and velocity pins also attached. This plate is inserted into the target chamber of a 72 mm bore light-gas gun with the sample face facing the projectile and the first active gauge element pair (one velocity and one impulse) nominally 1 mm beneath the impact surface of the sample. Subsequent gauge element pairs are located approximately at 1 mm additional depths for five gauge element pairs. Each gauge is inserted at an angle of 30°. The entire target assembly is immersed in a uniform magnetic field oriented normal to both the gauge element and the direction of projectile travel. Upon impact of the projectile and target the gauge elements are set into motion

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sequentially by the moving material in the sample and their motions in the static magnetic field induce a voltage proportional to the particle velocity of the flow. In addition, the impulse gauges in the gauge package also move through the magnetic field with the flow and acquire an induced voltage proportional to the time integral of the stress. Analysis of these data yield the pressure and particle velocity versus time for each of the five gauge pair (Lagrangian) positions as well as two records of wave arrival versus time from the particle velocity and impulse gauges separately. These data provide a record of the crushing dynamics of the aerogel sample as the matrix collapses under the application of pressure. This crushing is of fundamental importance in analysis of the data and in application of such materials in low pressure shock wave research.

3. DATA

Thus far, three MIV gauge shots have been fired. Other work includes Fabry-Perot interferometry and some preliminary spectroscopic studies. Only the gauge work will be reported here. Figure 1 shows the particle velocity records from shot 800. In Figure 2, the individual records are moved to a common time and the scale is magnified to show the early behavior of the flow. The principal feature of both Figures 1 and 2 is the overdrive apparent as the decaying spike in each of the individual records. In the last record of shot 800 the spike has nearly decayed away. This spike is present in all shots done to date and several explanations are being considered for the phenomenon. Included in these possibilities are gauge package assembly problems resulting in gaps and an initial "inert" constant-porosity response to the applied stress. The simplest explanation would appear to be gauge assembly problems. Nevertheless, out from under the spike one clearly sees the evolution of a very steady wave shape particularly in Figure 2. Assuming that the flow is steady (as verified by analysis of wave arrival times) allows a very simple analysis. Similar analysis has been done for the two other shots fired on these materials.

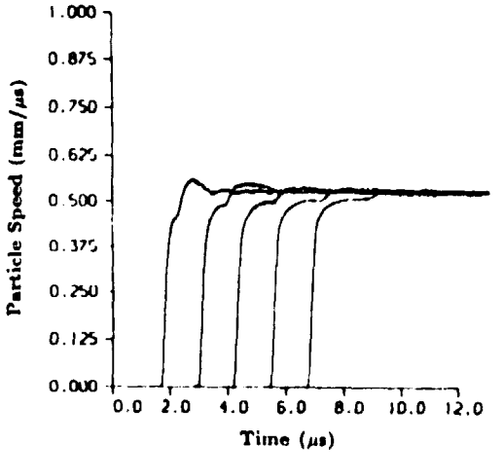

FIGURE 1
Shot record for shot #800. Particle velocities vs time at various positions.

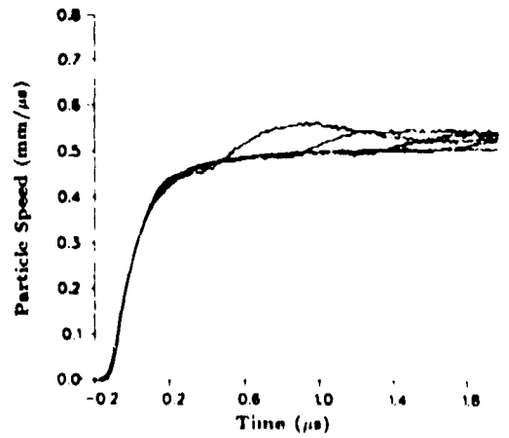

FIGURE 2
Shot records for shot #800. Records overlain to show similarity.

4. ANALYSIS

The assumption of steady flow allows an immediate reduction of the data and extraction of the distention parameter, α, defined as the ratio of the specific volume of the shocked porous material, V, to the specific volume at the same pressure and energy of the fully solid material, V_{sd}. Given the pressure and the internal energy from a point on the wave profile one solves for V_{sd} from the equation of state of the solid material. This procedure assumes that pressure is known as a function of volume and energy for the solid material. Thus, for a given record, one has particle

velocity as a function of time, $u_p(t)$, along the trace that yields pressure as a function of time, P(t), given a steady shock velocity, U_s. Similarly, from the mass conservation condition one gets density as a function of time, $\rho(t)$, again knowing particle velocity as a function of time from the data and having a steady shock velocity. Finally, the internal energy as a function of time, E(t), is given as one half the square of the particle velocity. With all of these data in hand and assuming an EOS for the full density SiO_2, one may solve for the specific volume as a function of the known pressure and internal energy, also, as a function of time. This procedure, then, gives one the distention, α, as a function of time at a given Lagrangian position in the flow. The mathematics of this procedure is displayed below:

$$P(t) = \rho_0 U_s u_p(t) \qquad 4.0.1$$

$$\rho(t) = \frac{\rho_0 U_s}{U_s - u_p(t)} \qquad 4.0.2$$

$$E(t) = \frac{1}{2} u_p(t)^2 \qquad 4.0.3$$

and

$$\alpha(t) = V_{sd}(P(t), E(t)) \qquad 4.0.4$$

where

$$V(t) = \frac{1}{\rho(t)} \, . \qquad 4.0.5$$

Having this simple formalism, one is in the position of carefully examining the behavior of α with t as suggested by Herrmann.[3] Figure 3 is a plot of the variation of α with t for shots 800 and 803 where the pertinent shot data are shown in Tables I and II.

TABLE I
Experimental Results
(Final Steady State Values)

Shot #	U_s (mm/μs)	u_p (mm/μs)	P (GPa)	V (cm³/g)
799	0.534	0.302	0.048	1.448
800	0.802	0.525	0.126	1.151
803	1.047	0.765	0.228	0.945

TABLE II
Initial Data

Shot #	Initial Density (g/cm³)	Projectile Velocity (mm/μs)
799	0.3	0.303
800	0.3	0.532
803	0.285	0.791

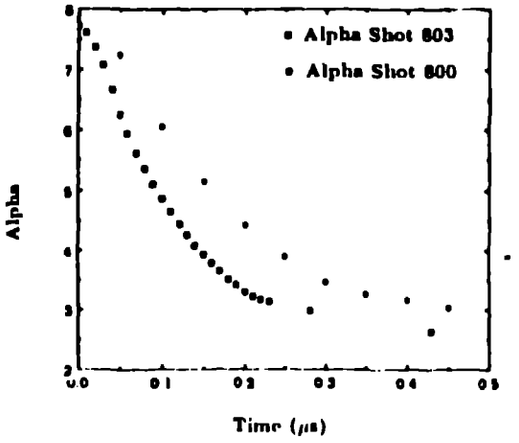

FIGURE 3
α vs time for shot #800 and #803.

A final comparison is also of interest and that is to look at the variation of α with P through the wave profile. It is important to note that this variation differs from the P - α variation suggested by Herrmann,[3] Boade[4] or Oh.[5] This variation of α with P is the immediate convolution of the rate of pore collapse with the current value of α and the pressure, P, through the steady wave. The exponential and polynomial expressions found in the literature cited above refer to the equilibrium value of the distention, α, compared to the equilibrium pressure, P, attained at the end of the shock process. Figure 4 shows the data from shot 800. Note that the data follow a nearly perfect straight line. As pointed out to us by Forest[6] this is the direct result of the momentum jump condition and the fact that the flow is quite steady as already assumed. This may be seen directly by

examination of equation 4.0.6, the result of combining equations 4.0.1, 4.0.2, and 4.0.4,

$$\alpha = \alpha_o \cdot \frac{P}{V_{sd}(\rho_o U_s)^2} \quad , \qquad 4.0.6$$

which admirably reproduces the slope seen in Figure 4 with V_{sd} set equal to V_{sd_o}. At the pressures attained in these experiments the additional assumption that fuzed quartz is nearly incompressible is excellent.

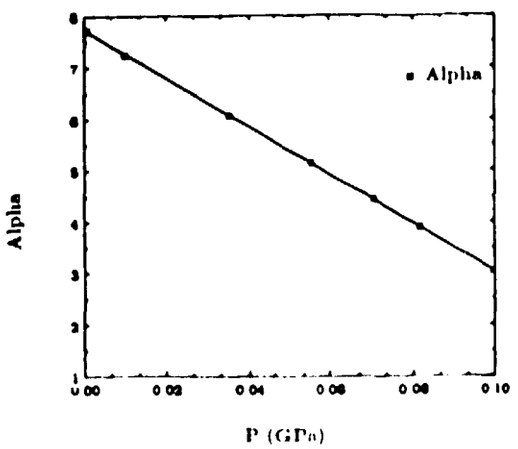

FIGURE 4
α vs P for shot #800

5. CONCLUSIONS

The experiments carried out thus far on these materials of extreme initial distention indicate that a significant rate process governs the steady wave behavior. In order to use the materials as shock wave standards in further EOS work on other materials such as high explosives, one must fully characterize the rate dependence of the pore collapse. From the data presented in Figure 3 it is evident that a fairly simple rate model for pore collapse in this material is directly available. In preliminary hydrocode modeling of these experiments we have used the rate

$$\frac{d\alpha}{dt} = k(\alpha_{min}(P) - \alpha)^n \qquad 5.0.1$$

with $\alpha_{min}(P)$ given by an estimate taken from the asymptotic value of α at the end of each of the three data sets fit to a simple polynomial in pressure. This procedure is working well thus far. Finally, it is of note to observe that the trend in the rate of pore collapse is that it becomes faster with increasing pressure. Thus it may be that at the higher pressures of some of the other work on these materials, such as that of Holmes,[7] the pore collapse may be so sudden that the wave is essentially sharp instantaneously validating the use of the jump conditions for analysis.

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